THERMAL EVOLUTION OF LOWER LIMBS DURING A REHABILITATION PROCESS AFTER ANTERIOR CRUCIATE LIGAMENT SURGERY

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Abstract:

Infrared thermography (IRT) is a safe and non-invasive tool used for examining physiological functions based on skin temperature (Tsk) control. The aim of this paper was to establish the probable thermal difference between the beginning and the end of the anterior cruciate ligament (ACL) rehabilitation process after surgery. For this purpose thermograms from 25 ACL surgically operated patients (2 women, 23 men) were taken on the first and last day of a six-week rehabilitation program. A FLIR infrared camera according to the protocol established by the International Academy of Clinical Thermology (IACT). The results showed significant temperature increases in the posterior thigh area between the first and the last week of the rehabilitation process probably due to a compensatory mechanism. According to this, we can conclude that temperature of the posterior area of the injured and non-injured leg has increased from the first to the last day of the rehabilitation process.

Key words: *injury, knee, temperature, thermal difference, ACL, infrared thermography, evolution*

Introduction

Since John Herschel obtained the first infrared image in 1840, which was called "thermogram", thermography has evolved considerably. In the 1970s, the computerized infrared imaging and the incorporation of colors in the thermograms increased the possibility of achieving better quantification and images that allowed thermography to penetrate into different areas (Birch, Branemark, & Nilsson, 1969; Dittmar, et al., 2006; Geneve, 1971; Gershon-Cohen & Haberman, 1968; Isard, Becker, Shilo, & Ostrum, 1972; Keyl & Lenhart, 1975; Leisman, 1990; Reinberg, 1975; Rothchild & Barnes, 1952; Steketee, 1976; Yang, 1988). Another great step forward was the possibility of analyzing and storing the images digitally. This breakthrough marked the beginning of quantitative thermography (Ring, 1990).

For many years research studies have described the capability of infrared thermography (IRT) to detect alterations in sports injuries by showing the temperature of the tissues involved (Keyl & Lenhart, 1975). The thermographic camera records heat emission as infrared radiation from each body part. Hyperthermic images appear when subcutaneous inflammatory reactions occur (Mangine, Siqueland, & Noyes, 1987). These reactions enhance the blood flow due to the increased cell activation.

Vasomotor and metabolic problems modify significantly the emission of body heat. The temperature of contralateral body areas or of the same area at different times can be compared to check how it evolves. The thermal alteration depends on the intensity of the underlying biological phenomenon that is occurring and on the size and depth of the involved tissue. Thermography does not reveal anatomic abnormalities, but the state of the tissues (Garagiola & Giani, 1990). It is a safe and a non-invasive tool.

In the early days of an acute injury there is a hyperthermic peak that lasts for at least 24 hours, and then temperature decreases gradually. No pain does not mean that the injury has fully recovered, and thermography can be effective to check whether the injured area is still affected (Garagiola & Giani, 1990).

The range of studies with well-founded results using thermography is quite wide, even in high-performance sports (Lopez, Cleary, Jones, & Zuri, 2008). Clark, Mullan, and Pugh (1977) significant results regarding the distribution of skin temperature during a race were obtained. Other studies have been conducted on, for example, patellar tendinitis (Mangine, et al., 1987) and ankle injuries (Specchiulli, Mastrosimone, Laforgia, & Solarino, 1991), or on gymnasts (Caine, Cochrane, Caine, & Zemper, 1989; Meeusen & Borms, 1992). Hildebrandt and Raschner (2009) applied thermography on alpine skiers with ACL tears, observing significant differences in the thermograms of the injured and non-injured leg. The thermogram of the affected knee showed a massive increase of hyperthermia under the patella that represented the inflammatory process. After six months, the knee still showed a thermal imbalance when compared to its contralateral joint.

The purpose of this study was to compare the skin temperature (Tsk) of the lower limbs before and after a six-week ACL post-surgey rehabilitation program. Infrared thermography was the selected tool.

Material and methods

Subjects

Data collection began in November and finished in May 2011 in accord with each subject´s rehabilitation schedule. The total number of recruited subjects was 34, but nine subjects were excluded from the study due to a lack of continuity or other associated serious injuries that could bias the study. Therefore, the final sample consisted of 25 subjects (age: 32.68±8.6 years, 23 men and 2 women) of which 92% were injured practicing sports, e.g. football, skiing and racket sports in most cases. The remaining 8% were injured in traffic accidents. An average of 34.16±12.02 days passed from the date of the operation untill the beginning of rehabilitation.

Instruments

A FLIR T-335 camera (FLIR Systems, Sweden) with a thermal sensitivity of 0.50 mK, an error of ±2% reading in degrees Celsius (°C), and a resolution of 340x260 pixels was used, mounted on a tripod. The subject stood on a platform to be raised from the floor surface in front of a 100x200 cm screen to create a homogeneous background without reflections. The environmental conditions of temperature, humidity and atmospheric pressure were registered with a portable weather station Oregon Scientific BAR908HG.

The surface area of the measuring room was approximately 70 m^2, with an average temperature of 21 °C±1.9 °C, always within the ideal values range for thermographic studies in humans (Garagiola & Giani, 1990; IACT, 2002; Ring & Ammer, 2000). The distance between the position of the patient and the camera for data collection was set at 2.5 meters (Garagiola & Giani, 1990; IACT, 2002; Ring & Ammer, 2000).

Humidity can also affect the data collection (Reinikainen & Jaakkola, 2003) and atmospheric pressure. Those parameters remained stable during the study with average values of 56±2.3% for humidity (Zontak, Sideman, Verbitsky, & Beyar, 1998) and 938±5 hPa for atmospheric pressure.

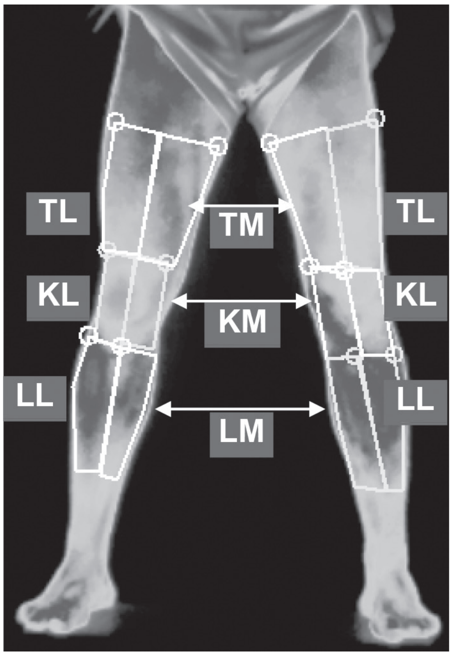
Infrared pictures were always taken between 9:00 and 10:00 a.m. Pictures were taken in two phases of rehabilitation: the first was taken when the subject came to the rehabilitation room for the first time, prior to any rehabilitation exercise in order to obtain images of the subject in a complete state of rest. The second picture was taken on the last day of the rehabilitation of each subject. The rehabilitation program lasted six weeks for every subject. Our aim was to observe if the skin temperature distribution had changed between the two time points. All evaluations took place at the San Carlos Clinical Hospital Rehabilitation Center.

At each evaluation different influencing factors (IACT, 2002; Ring & Ammer, 2000) were registered: application of creams, massage or other treatment, sun bathing or a shower in the previous eight hours, consumption of a big meal, coffee, smoking or alcohol in the previous six hours. An acclimatization time of ten minutes was respected prior to data collection (Garagiola & Giani, 1990; Zontak, et al., 1998).

For measurement, the subjects remained in their underwear, or in shorts held at the hips with tweezers. Two pictures (thermograms) were taken at each evaluation: an anterior and a posterior view of the lower limbs. Twelve regions of interest (ROI) were analyzed on each leg, six in the posterior (P) and six in the anterior (A) view (Figure 1). The six areas were distributed in pairs along the lower member (medial=M and lateral=L). Two areas form the area of the knee (knee lateral=KL and knee medial=KM), two in the thigh, (thigh lateral=TL and thigh medial=TM) and the remaining two in the lower leg (leg Lateral=LL and leg medial=LM). It was also considered whether the area was on the injured (I) or non-injured (NI) leg (Figure 1).

Lee and Cohen (2008) analyzed six areas of interest on each leg, three on the anterior view and three on the posterior view - thigh, knee and lower leg. In our study we divided each of their areas into two areas (a medial and a lateral one), as explained previously. But later, global data of the anterior and posterior view were analyzed as a single area.

After selecting the ROI, the thermograms were analyzed with Therma CAM Reporter 8 Software to extract the temperature data of every ROI (maximum, minimum, average and standard deviations). The values obtained from the ROI in the first data collection were compared with the values of the same areas collected in the second measurement (Bertmaring, 2006).



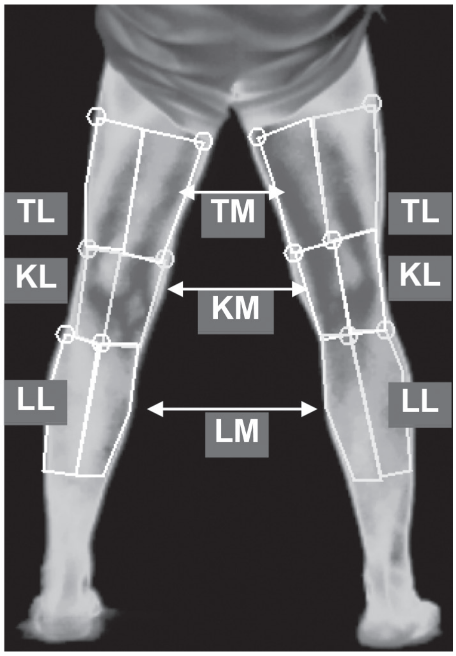


Figure 1. Thermal images with the distribution of the six areas of the anterior view (left) and six areas of the posterior view (right): TL (thigh lateral), TM (thigh medial), LL (lower leg lateral), LM (lower leg medial), KL (knee lateral), KM (knee medial) of the injured (I) and non-injured (NI) leg.

Testing procedures

All the participants formally agreed to collaborate in the research and signed an informed consent. An Ethical Committee from the Technical University of Madrid (UPM) granted the permission to conduct this research with thermography on human beings in different populations. Data were collected in a public hospital of Madrid named Carlos III Public Hospital. While the subjects were filling in the questionnaires, researchers were present to answer any questions and resolve any issue.

Then, atmospheric standard conditions were checked. The subject remained at rest but standing for at least ten minutes before the pictures were taken. Afterwards, the images were processed with Therma CAM Reporter 8 through predefined templates to distinguish thermal features of different leg areas. This program provides statistical information about each area (average temperature, maximum and standard deviation). Finally, these data were processed with the statistical program SPSS (SPSS Worldwide Headquarters, Chicago, IL), v.15.0.

Statistical analysis

The data were sorted and managed with Microsoft Excel 2007. Firstly, we divided each leg into 12 regions of interest (ROI), six anterior view and six posterior view: two areas of the thigh (lateral and medial), two areas of the knee (lateral and medial) and two areas of the lower leg (medial and lateral). Average, maximum temperature and standard deviation of each area were calculated with Therma CAM Reporter 8. In order to compare our data to other studies, we simplified the recorded data in only six areas on each leg, three anterior and three posterior areas (thigh, knee and lower leg). Finally, we analyzed the global data of the leg by calculating the average and maximum temperature of the front and the back of each limb (injured and non-injured) with SPSS for Windows, v.15.0 (SPSS Worldwide Headquarters, Chicago, IL). Descriptive data were calculated and the Student's *t*-test for dependent samples was performed to establish differences in the variables between the first and the last week of the rehabilitation process in both legs with a confidence level of 95%.

Results

Analysis of temperature

Table 1 shows temperature averages of the areas of the injured leg. Based on that table, even before statistical analysis, it is evident that most differences in temperature between the first and the last week relate to a higher temperature of the leg on the first week. This would mean that in the first week the temperature seems to have been higher than in the last week.

Table 2 shows temperature averages of the same areas of the non-injured leg. In the anterior view of the non-injured leg, the bigger difference occurred in the lateral thigh (t_{24}=1.975, p=.06). No statistically significant changes in the temperature were obtained between the first and the sixth week of rehabilitation in any of the anterior areas. In

Table 1. Injured leg. Average values of the anterior (A-) and posterior (P-) view: TL (thigh lateral), TM (thigh medial), LL (lower leg lateral), LM (lower leg medial), KL (knee lateral), KM (knee medial)

Regions of Interest (ROI) **Injured Leg**	AVERAGE TEMPERATURES					MAXIMUM TEMPERATURES				
	First Week		Last Week		Dif.	First Week		Last Week		Dif.
	Mean	SD	Mean	SD		Mean	SD	Mean	SD	
A-TL	29.79	1.15	29.40	1.29	0.39	31.00	1.08	30.58	0.97	0.41
A-TM	29.62	1.34	29.06	1.27	0.57	31.26	1.23	30.71	0.90	0.55
A-LL	31.53	1.01	31.59	0.75	-0.06	32.98	0.92	32.94	0.62	0.04
A-LM	31.31	1.13	31.25	0.85	0.06	32.94	1.00	32.77	0.68	0.17
A-KL	30.24	1.36	30.00	0.92	0.24	32.20	1.19	32.00	0.77	0.20
A-KM	30.54	1.11	30.14	0.90	0.40	32.37	1.13	32.04	0.81	0.33
P-TL	30.22	1.38	30.04	1.13	0.18	31.28	1.17	31.21	0.91	0.07
P-TM	30.65	1.27	30.32	1.07	0.33	31.76	1.09	31.59	0.91	0.17
P-LL	30.76	0.95	30.86	1.15	-0.09	31.92	0.88	32.11	1.05	-0.20
P-LM	30.94	0.84	31.02	1.16	-0.07	31.98	0.88	32.24	1.08	-0.26
P-KL	31.08	0.98	30.92	1.10	0.16	32.53	0.90	32.44	1.00	0.08
P-KM	31.16	0.98	30.99	0.91	0.18	32.54	0.82	32.40	0.85	0.13

Legend: Mean – average, SD – standard deviation, Dif. – difference

Table 2. Non-injured leg. Average values of the anterior (A-) and posterior (P-) view: TL (thigh lateral), TM (thigh medial), LL (lower leg lateral), LM (lower leg medial), KL (knee lateral), KM (knee medial)

Regions of Interest (ROI) **Non-injured leg**	AVERAGE TEMPERATURES					MAXIMUM TEMPERATURES				
	First Week		Last Week		Dif.	First Week		Last Week		Dif.
	Mean	SD	Mean	SD		Mean	SD	Mean	SD	
A-TL	30.28	1.10	29.92	1.19	0.36	31.45	0.96	30.99	0.89	0.46
A-TM	30.11	1.27	29.67	1.31	0.44	31.51	1.09	31.44	2.73	0.08
A-LL	31.67	0.89	31.77	0.82	-0.10	32.77	0.85	32.89	0.65	-0.12
A-LM	31.18	1.10	31.13	1.08	0.05	32.48	1.08	32.32	0.80	0.16
A-KL	29.38	0.99	29.28	1.09	0.09	31.44	1.08	31.28	0.94	0.16
A-KM	29.75	1.02	29.56	1.17	0.18	31.21	0.90	31.17	2.14	0.04
P-TL	30.44	1.29	30.11	1.21	0.33	31.71	1.07	31.56	1.04	0.15
P-TM	31.04	1.40	30.84	1.31	0.20	32.24	1.09	32.02	1.04	0.22
P-LL	31.19	0.92	31.21	1.12	-0.02	32.10	0.99	32.30	1.04	-0.20
P-LM	31.36	0.91	31.32	1.07	0.04	32.19	0.88	32.32	0.98	-0.14
P-KL	31.34	0.89	31.30	1.12	0.04	32.68	0.75	32.77	0.84	-0.08
P-KM	31.40	0.98	31.19	1.07	0.21	32.59	0.88	32.68	0.91	-0.09

Legend: Mean – average, SD – standard deviation, Dif. – difference

Table 3. Average temperature difference for the thermal profile of the postoperative period of the ACL between the first and the last week of rehabilitation

		ANTERIOR VIEW (AV)			POSTERIOR VIEW (PV)		
	Week	Thigh	Knee	Leg	Thigh	Knee	Leg
INJURED LEG	FIRST WEEK	29.71 ºC	30.39 ºC	31.42 ºC	30.4 ºC	31.12 ºC	30.85 ºC
	LAST WEEK	29.23 ºC	30.1 ºC	31.42 ºC	30.18 ºC	30.95 ºC	30.94 ºC
	Dif. First-Last	0.48	0.29	0	0.22	0.17	-0.09
NON-INJURED LEG	FIRST WEEK	30.19 ºC	29.56 ºC	31.42 ºC	30.74 ºC	31.37 ºC	31.28 ºC
	LAST WEEK	29.8 ºC	29.42 ºC	31.45 ºC	30.48 ºC	31.25 ºC	31.27 ºC
	Dif. First-Last	0.39	0.14	-0.03	0.26	0.12	0.01

Legend: Dif. – difference

Table 4. General averaged skin temperature (Tsk) differences for the injured and non-injured leg between the first and the last week. (t_{24}=-1.23; p=.66)

		ANTERIOR VIEW		POSTERIOR VIEW	
		Mean	SD	Mean	SD
INJURED LEG	FIRST WEEK	30.50 ºC	1.07	30.79 ºC	1.02
	LAST WEEK	30.25 ºC	0.84	30.69 ºC	0.82
	Dif.	0.25 ºC		0.1 ºC	
NON-INJURED LEG	FIRST WEEK	30.39 ºC	1.03	31.13 ºC	1.02
	LAST WEEK	30.22 ºC	1.01	31.0 ºC	0.8
	Dif.	0.17		0.13 ºC	

*Table 5. Maximum skin temperature (Tsk) differences in the injured and non-injured leg between the first and last week. (*p<.05 **p<.01)*

		ANTERIOR VIEW		POSTERIOR VIEW	
		Mean	SD	Mean	SD
INJURED LEG	FIRST WEEK	32.17 ºC	0.93	31.9 ºC	0.88
	LAST WEEK	31.95 ºC	0.76	32.31 ºC	0.78
	Dif.	0.22 ºC		-0.42 ºC*	
UNINJURED LEG	FIRST WEEK	31.77 ºC	0.9	32.14 ºC	0.9
	LAST WEEK	32.7 ºC	0.8	32.7 ºC	0.65
	Dif.	0.07 ºC		-0.56 ºC**	

the posterior area the most prominent value was (t_{24}=1.087; p=.28) between the medial thighs. Also, no significant changes in the temperature between the first and the last week of rehabilitation were obtained in the posterior view.

Thermographic profile of the operated ACL before and after the rehabilitation program

Table 3 shows a summary of the values obtained within three areas per view. The medial and lateral areas of each anatomical part have been joined to optimize the analysis. We found differences of 0.48 ºC between the first and the last week in the thighs of the anterior area.

As we can detect the temperature difference within the thermograms, and the body behaves with global responses, we joined the areas into only four: *anterior injured*, *posterior injured*, *anterior non-injured*, and *posterior non-injured* (Table 4 and Table 5).

The Student's *t*-test for dependent samples showed that there were no significant changes in global average temperatures between the first and the last week of rehabilitation. The most prominent value was (t_{24}=-1.23, p=.66) between the posterior areas of the non-injured leg (Table 4).

The *t*-test for dependent samples showed that there were significant differences in maximum temperatures (Table 5) in the posterior area between the first and the last week of rehabilitation in both the injured and non-injured leg; t_{24}=-2.24 (p=.034) and t_{24}=-3.33 (p=.003), respectively. In the anterior view, however, no significant differences were found t_{24}=1.10; (p>.05). In the non-injured leg this difference was bigger.

Discussion and conclusions

Many studies have used thermography as a tool to help athletes and have defended its use in sport and health (Akimov, et al., 2009; Bagarone, 1987; BenEliyahu, 1990; BenEliyahu, 1992; Bertmaring, 2008; Čoh & Širok, 2007; Ferreira, et al., 2008; Garagiola & Giani, 1990, 1991; Gómez, Sillero-Quintana, Noya, & Pastrano, 2008; Gross, Schuch, Huber, Scoggins, & Sullivan, 1989; Hildebrandt & Raschner, 2009; Hildebrandt, Raschner, & Ammer, 2010; Hildebrandt, 2010; Katz, et al., 2008; Keyl & Lenhart, 1975; Mangine, et al., 1987; Pochaczevsky, 1987; Rochcongar & Schmitt, 1979; Roehl, et al., 2009; Tkacova, 2010; Vainer, 2000). Our study focused on thermography as a tool for monitoring the injury recovery process through the comparison of the initial and the final state of temperature in the same leg (injured and non-injured leg separately) at two different time points. In the average data of Table 1 (injured leg) we observe the maximum temperature decrease of 0.56 ºC between the first and the last week (A-TM). We can also recognize a decrease in temperature from the first to the last week in other anterior areas as thigh lateral (A-TL), knee lateral (A-KL) and knee medial (A-KM). In the posterior view the biggest decrease occurred between the thigh medial areas (P-TM). There were only three areas where the last week temperature was higher than the temperature in the first week, but the difference was less than 0.1 ºC.

According to the maximum data from Table 1, the biggest difference corresponds also to the anterior thigh medial (A-TM) with 0.55 ºC. However, the posterior view shows that in some areas (P-LL and P-LM) the temperature between the first and the last week has increased over 0.2 ºC.

In Table 2, it can be seen that most differences in temperature between the first and the last week relate to a higher temperature of the non-injured leg in the first week. In the average data a maximum difference of 0.44 ºC between the same side areas of the anterior thigh medial (A-TM) can be noticed. We can recognize a decrease in temperature from the first to the last week in other anterior areas as thigh lateral (A-TL). In the posterior view, the biggest decrease occurred between the thigh lateral and medial areas (P-TM, P-TL). There are two areas in which the temperature was higher in the last week than in the first week, but the differences were less than 0.1 ºC. In the maximum data, the biggest difference corresponds also to the anterior thigh lateral (A-TL) with 0.46 ºC, while the thigh medial difference decreased by 0.08 ºC. However, the posterior view showed that both in the knee and lower leg areas the temperatures in the last week were higher than in the first week.

In Table 3 we have joined the medial and lateral aspects of each area, thus obtaining six areas per leg and three for each view (Lee & Cohen, 2008). In Table 4 a simplified view in just one area is presented. Data show the greatest difference in the thigh in both anterior and posterior view in Table 3. In both cases the temperature of the last image is lower than the temperature of the first image. Table 4 also shows a higher temperature on the first day than on the last. This data indicates that, indeed, the temperature is falling, probably due to the drop of the blood flow produced by an improvement in the injury state (Garagiola & Giani, 1990; Mangine, et al., 1987).

The data in Table 5 show significant differences in maximum values between the initial and the final state of temperature in the posterior areas of both legs. The temperature had increased during the recovery process. Barker, Hughes and Babski-Reeves (2006) used thermal imaging to detect thermal changes after physical activity. They took pictures at different times of the activity to compare their evolution. They concluded that thermography was sensitive to thermal changes during the physical tasks, so it can detect the blood flow demand that produces the thermal changes and responses. Hunold, Mietzsche, and Werner (1992) came to the same conclusion after a study where pictures were taken before, during and after a ten-minute ergometer exercise. They could register temperature changes over 3 ºC.

Our results show that there was a different thermal behavior of the anterior and posterior view of legs as explained above. We believe it was due to the offset and muscle compensation which occurred during or prior the recovery period because subjects tried to protect the injured leg by changing the mechanics of walking and gait. We noticed that while walking they loaded their healthy legs more. This extra work could be the reason why the non-injured leg was also affected by an increase of temperature in the posterior area prior and during the rehabilitation process.

Thermography can be a good tool when a rapid and objective monitoring of the structures damaged by an injury is required. Tables from our study show the differences between temperatures, but in some cases they are not accompanied with statistically significant results. The experience of working with thermography tells us that although there are no statistically significant differences, this does not imply that differences do not exist. So, when drawing the line between a healthy and damaged (or not fully recovered) structure we must be extremely cautious.

This study demonstrates that there was a temperature increase in the posterior area of both the injured and non-injured leg between the first and the last week of the rehabilitation process after the ACL surgery. Significant differences were not found in any other measures, so we can conclude that the temperatures of other areas were similar in the first and the last week of rehabilitation, meaning the observed body structures had not fully recovered during the rehabilitation period. Thermography has applicative value as a diagnostic method in the evaluation of different phases of the rehabilitation process after athletic injuries. Future research should contribute to more efficient use of data collected during different rehabilitation protocols.

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TEMPERATURNE PROMJENE DONJIH EKSTREMITETA TIJEKOM REHABILITACIJSKOG POSTUPKA NAKON OPERACIJE PREDNJE UKRIŽENE SVEZE

Infracrvena termografija je siguran i neinvazivan način provjere fizioloških funkcija, baziran na kontroli temperature kože. Cilj ovog rada bio je utvrditi moguće toplinske razlike između vrijednosti zabilježenih na početku i na kraju rehabilitacijskog procesa nakon operacije prednjih križnih ligamenata. Iz tog su razloga napravljeni termogrami na 25 operiranih ispitanika (2 žene, 23 muškarca). Razmak između mjerenja bio je šest tjedana, a ispitanici su mjereni FLIR infracracrvenom kamerom prema protokolu International Academy of Clinical Thermology (IACT). Rezultati su pokazali značajno povećanje temperature u području stražnje strane natkoljenice između prvoga i posljednjega tjedna rehabilitacije, vjerojatno zbog pojave kompenzacije u mišićnoj aktivnosti. Može se zaključiti da se temperatura stražnje strane natkoljenice ozlijeđene, ali i zdrave noge značajno povećala između prvog i šestog tjedna rehabilitacijskog procesa.

Ključne riječi: *ozljeda, koljeno, temperature, termalna razlika, prednji križni ligament, infracrvena termografija, razvoj*